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Changes in the thermal structure of freshwater lakes within Cape Cod National Seashore (Massachusetts, USA) from 1996 to 2014

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ABSTRACT

Freshwater lakes throughout many parts of the world have undergone substantial warming in response to climate change. In southern New England, within Cape Cod National Seashore (CCNS; Massachusetts, USA), numerous freshwater lakes known as “kettle ponds” scattered throughout the landscape have exhibited increasing surface water temperatures for the past 2 decades. In this study, we examined changes in summer air temperatures, wind speeds, underwater light transmission (3 of the primary factors influencing lake thermal structure), and the temperature profiles of 9 ponds from 1996 to 2014. Mean, minimum, and maximum daily air temperatures all increased significantly while mean daily maximum and average wind speeds declined. The attenuation of light to 50% and 25% of surface intensities occurred at significantly greater depths in 7 ponds, whereas the depths at which light transmission was 1% of surface values increased in 3 ponds. Thermocline depths became shallower in 2 ponds while temperature between surface and bottom waters increased in 6 ponds. Bottom waters exhibited significant cooling in 4 ponds while Schmidt stability values (which indicate the strength of thermal stratification) increased in 5 ponds. Thermocline depth among ponds was positively correlated with light transmission variables for the majority of years between 1996 and 2014, and all temperature variables were significantly correlated with mean daily air temperature. The patterns indicate a general strengthening of thermal stability during the summer and seem to be related to increasing local air temperatures and reduced wind speeds. Implications of changes in the thermal properties of CCNS ponds are discussed in the context of potential physical, chemical, and ecological processes.

KEYWORDS

Cape Cod; climate change; kettle ponds; stratification; temperature; thermal stability; thermocline

Introduction

Climate change is one of the most critical environmental concerns of the 21st century, and a vast number of ecosystems have already been, or are likely to be, impacted by its progression. The mechanisms and outcomes of climate change, however, are exceedingly complex and may be disparate across various spatial and temporal scales. In the northeastern United States, multidecadal trends in a number of climate variables indicate significant atmospheric warming (Frumhoff et al. 2007, Pilson 2008, Rogers and Young 2014), which has had a cascading effect on ecosystem processes across many different landscapes. In terrestrial environments, maximum river flows have shifted to earlier dates, lakes are becoming ice-free earlier in the year, less precipitation is falling as snow, and extreme precipitation events are becoming more frequent (Hodgkins et al. 2002, 2003, Hayhoe et al. 2007). Moreover, growing seasons are lengthening (Christiansen et al. 2011), and many flowering plant taxa are blooming earlier in spring (Wolfe et al. 2005).

Climate warming is significantly impacting the earth's oceans and estuaries (e.g., Scavia et al. 2002, Toggweiler and Russell 2008), rivers (Nijssen et al. 2001), and lakes (O'Reilly et al. 2003, 2015, Adrian et al. 2009). Lakes in particular can be influenced both directly and indirectly, and their responses may be highly variable, depending on a variety of factors such as size (Scheffer and van Nes 2007), trophic state (Fee et al. 1996), and surrounding land use (Pham et al. 2008). In many cases, increasing temperatures have been observed throughout the extent of the water column (Livingstone 2003). In others, the effect has been limited to the surface, with little or no change, or even cooling, in lake-bottom water temperatures (Alcocer and Lugo 2003). Differences between surface and bottom water temperatures are generally increasing, which enhances the strength and duration of thermal stability (Arvola et al. 2009, Stainsby et al. 2011, Hadley et al. 2014). In addition, both shoaling and deepening of the thermocline has been observed (Alcocer and Lugo 2003, Healey 2011).

Wind is another factor that can influence lake thermal properties. Winds drive vertical mixing, and evidence shows that summer wind speeds have decreased in southern New England since 1984 (Pilson 2008). Moreover, the regrowth of surrounding tree and understory vegetation in this region following extensive forest clearing in earlier centuries further impedes winds across inland waterbodies (Andrew et al. 2008, Read et al. 2012, Woolway et al. 2016). Light transmission also plays a role in thermocline structure in that higher light penetration generally translates to deeper thermoclines and vice versa (Mrozek-Lejman and Karbowiczek-Gratkowska 1997, Pérez-Fuentetaja et al. 1999, Gaiser et al. 2009). Light transmission itself is influenced by a number of factors, including dissolved organic carbon (DOC; Bukaveckas and Robbins-Forbes 2000), phytoplankton species composition and biomass (Vaillancourt et al. 2004), and suspended particulates (Karlsson et al. 2009, Bachmann et al. 2017).

Of the many studies of temperature trends in large lakes (e.g., Austin and Colman 2007, Schneider et al. 2009, Schneider and Hook 2010, Mason et al. 2016, Zhong et al. 2016), few have focused on small systems, which may respond quite differently (O'Reilly et al. 2015, Winslow et al. 2015). Moreover, small lakes are considered disproportionately important in regulating biogeochemical cycles at a global scale (Tranvik et al. 2009, Cole et al. 2011, Read and Rose 2013). At Cape Cod National Seashore (CCNS; MA, USA), numerous small (median size <8 ha) lakes occur throughout the landscape. Known locally as “kettle ponds,” these waterbodies were created by melting blocks of ice left behind on the sandy outwash plain during the last glacial retreat roughly 18 000 years ago. Kettle ponds are important natural resources that support unique assemblages of flora and fauna, including a number of state-listed rare species (LeBlond 1989, Somers 1999, Portnoy et al. 2001). They are also a major attraction for visitors who value their aesthetic qualities and recreational opportunities. Within CCNS, the water quality of these ponds has been consistently monitored since the mid-1990s. Since that time, surface waters have warmed by ~2 °C during July and August, coincident with a rise in pond pH due to a reduction in rainfall acidity (Smith et al. 2016).

Regardless of the mechanism(s), changes in lake thermal structure can impact numerous ecological processes, including hypolimnetic oxygen concentrations (Stefan et al. 1993, Jankowski et al. 2006, Foley et al. 2012, Sahoo et al. 2013), internal nutrient release and bioavailability (Williamson et al. 2009, Trolle et al. 2011, Sahoo et al. 2013), species composition, biomass, and timing of algal blooms (Parker et al. 2008, Paerl and Huisman 2009, Winder and Sommer 2012). They can also affect overall habitat suitability from zooplankton to higher organisms

within the ecosystem (Winder and Schindler 2004a, 2004b). In this study, we examined vertical profiles of light transmission, wind speed, and pond temperatures (surface to bottom) during July and August over the past ~2 decades. The main objective was to assess whether lake thermal structure has undergone significant change during this time and evaluate links with possible driving mechanisms. We discuss the results in the context of potential ecological consequences, predictions of the future state of these ponds, and relationship of these changes to local atmospheric conditions.

Materials and methods

Study area

Nine freshwater kettle ponds within CCNS were examined in this study, including Duck, Dyer, Great-T, Great-W, Gull, Herring, Long, Ryder, and Slough (Fig. 1), representing a wide range of physical attributes (Table 1). The ponds are situated within the glacial outwash plain sediments of outer Cape Cod, composed of mostly granitic sand and gravel.

Air temperature and wind speed

Air temperature and wind data were derived from the Weather Underground station for the West Chatham airport, Massachusetts (KCQX), ~32 km from the CCNS kettle ponds (Fig. 1). Means of daily maximum (AT_{MAX}), average (AT_{AVE}), and minimum (AT_{MIN}) air temperatures during July were determined for 1996–2014 because this analysis focuses on water sampling conducted in August, and ponds could not be influenced by air temperatures subsequent to their sampling date. Similarly, mean daily maximum (W_{MAX}) and average (W_{AVE}) wind speeds for July–August were calculated, as were mean daily maximum gust speeds (G_{MAX}).

Water temperature and light transmission

All pond temperature and light transmission data were collected as part of the Cape Cod Ecosystem Monitoring (CCEM) program that has been conducted for several decades. Vertical profiles of water temperatures have been collected at fixed stations marking the deepest point of each pond. The data were collected at 1 m depth increments (with an additional sample collected at 0.5 m representing surface conditions) from the surface to bottom using pre-calibrated multiparameter Hydrolab water quality sondes from 1996 until 2002 and YSI sondes thereafter. The most complete temperature records spanned the period from 1996 to 2014. Depth profiles (1 m intervals)

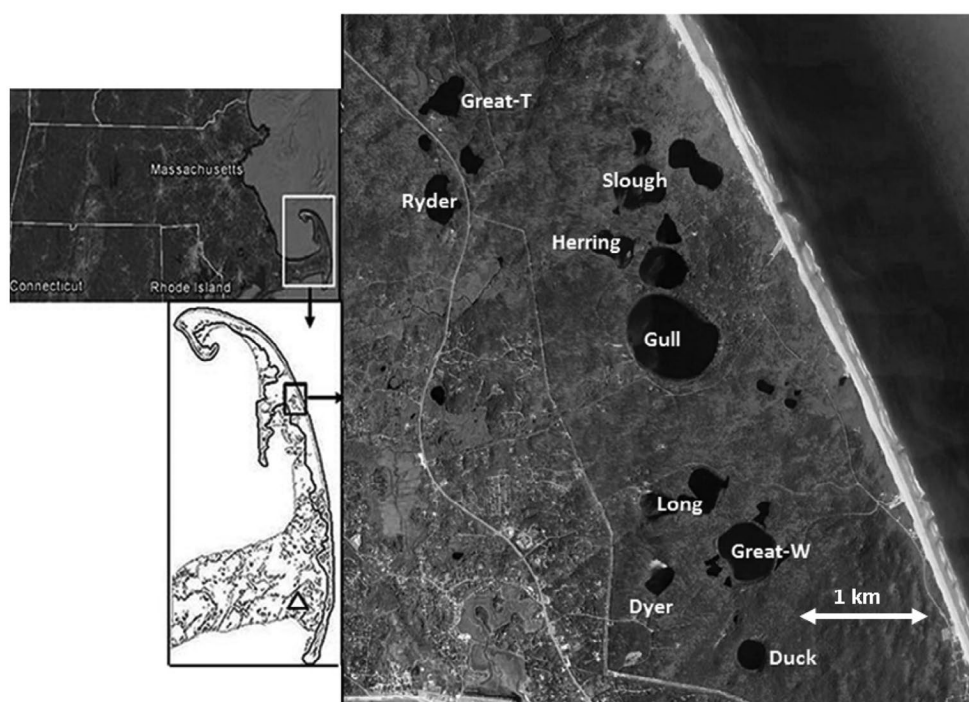


Figure 1. Massachusetts (upper left), Cape Cod (bottom left; polygon defines the boundary of CCNS), and the kettle ponds within CCNS analyzed in this study (right). Triangle indicates location of Chatham, where air temperature was acquired through the Weather Underground database (<https://www.wunderground.com/us/ma/chatham>).

Table 1. Physical characteristics of the CCNS kettle ponds analyzed in this study (from Portnoy et al. 2001).

Pond	area (m ²)	volume (m ³)	max depth (m)	mean depth (m)	aspect ratio
Duck	48 180	291 776	18	6.1	12.2
Dyer	46 562	239 327	10	5.1	21.6
Great-T	66 363	270 439	11	4.1	23.4
Great-W	1 71 748	913 599	16	5.3	25.9
Gull	4 44 609	3 751 049	19	8.4	35.1
Herring	78 385	213 364	4	2.7	70.0
Long	1 45 880	1 129 461	15	7.7	25.5
Ryder	79 585	500 170	10	6.3	28.2
Slough	5 622	43 528	8	7.7	9.4

of percent transmittance of photosynthetically active radiation (PAR) were also measured using an LI-COR LI-1400 light meter equipped with 2 underwater quantum sensors (LI-192SA). The transmission data encompassed years 1999–2014. The data were used to calculate the depths at which 50% (TR_{50}), 25% (TR_{25}), and 1% (TR_1) of surface sunlight remained for each pond in August, accomplished by fitting exponential curves (which provided the best fit with R^2 values >0.9) to the data and then using these formulae to calculate the above variables.

Four variables describing pond thermal properties were analyzed: (1) thermocline depth (TC_D), defined as the bottom of the 1 m depth interval where the largest decline in temperature occurs along the vertical profile (Parker et al. 2008, Fortino et al. 2014); (2) difference in

temperature between surface (1 m depth) and bottom waters (SB_{DIFF}); (3) bottom water temperatures (BW_T); and (4) Schmidt stability (SS), a stratification metric calculated from vertical temperature profiles and bathymetry. Note that temporal trends in July–August surface water temperatures (T_{SW}) in the individual ponds were previously analyzed by Smith et al. (2016). In this analysis, the grand means (mean of all ponds) of August-only surface water temperatures are reported and interpreted.

Statistical analyses

Only water temperature data from August were analyzed because they represent the time period when temperatures are maximal and, consequently, when ponds are most strongly stratified. When multiple vertical profiles were taken in a particular year, values from dates nearest the middle of August (15th) were used. Thus, the time series consisted of one data point per year of record so that differences in sample size for certain years would not produce artificially skewed regressions. Furthermore, because data were missing for certain years, the analyses were confined to a continuous time series where no more than 2 consecutive years of missing values occurred. As such, large data gaps through time could not unduly influence trend analyses, although this constrained the data to 1996–2014.

Schmidt stability metrics, which indicate the amount of energy needed to mix the water column, were calculated (Schmidt 1928, Idso 1973, Weinberger and Vetter 2014). Because this index requires bathymetry to be known, however, values for Long and Slough ponds could not be determined because these sites have no bathymetric data. With the exception of thermocline depth, all data met the assumptions of normality/homoscedasticity and were analyzed by linear regression for temporal trends (JMP 10.0.2). To determine the magnitude of changes in variables over time, the resulting regression equations were used to calculate initial and final values of the time series along the trend lines. From these data, absolute change and percentage change were calculated. These change values, as well as the actual values of each temperature variable from the last sampling in 2014, were plotted against pond physical attributes, including pond area, volume, mean depth, maximum depth, and pond aspect ratio (defined as the square root of area/maximum depth). Pond temperature variables were also plotted against mean, maximum, and minimum daily air temperatures in July because lake temperatures can only be influenced by conditions prior to the measurement dates in August. TC_D and many of the above physical variables were non-normal and required the use of nonparametric Kendall τ tests for analyses (JMP 10.0.2). All statistical values for R^2 , Kendall τ , p , and Δ

(total magnitude of change based on regression equations) are presented in the figures.

Results

Air temperature and wind speed

Mean daily AT_{MAX} , AT_{AVE} , and AT_{MIN} all exhibited strong increases from 1996 to 2014, although the trend for AT_{MIN} was not statistically significant, mainly because of an anomalously low value in 2014 (Fig. 2). Values of change over this time period were 1.7 °C (0.11 °C/yr), 1.4 °C (0.07 °C/yr), and 1.2 °C (0.06 °C/yr), respectively. Mean and maximum wind speeds declined significantly from 1996 to 2014, which both decreased by 0.8 m/s (Fig. 2). By contrast, gust strength did not show a significant trend.

Light transmission

Six of 9 ponds (Dyer, Great-T, Gull, Long, Ryder, Slough) exhibited significant positive trends in TR_{50} and TR_{25} depths, indicating increasing water clarity (Table 2). TR_1 depths also increased in 2 ponds (Long, Ryder) but decreased in one (Dyer; Table 2). The grand means (all ponds) of TR_{50} and TR_{25} depths increased by 0.5 m and 0.7 m, respectively, whereas TR_1 depths increased but not significantly (Fig. 3).

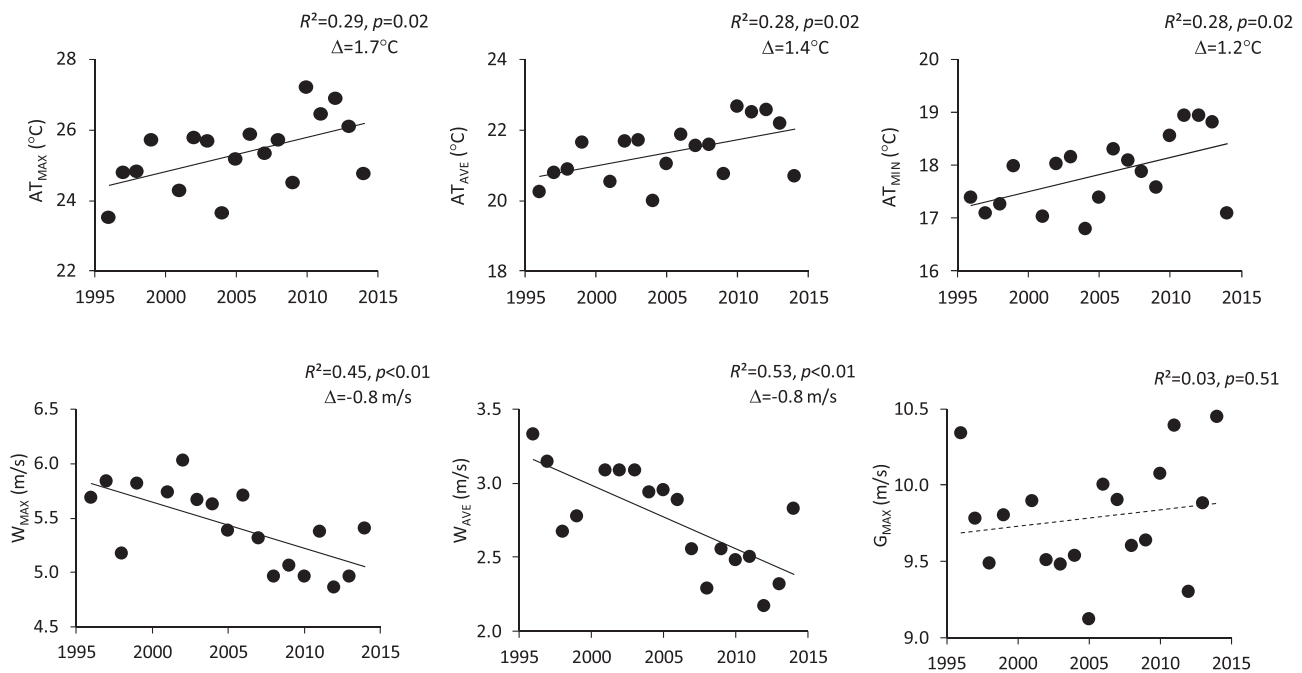


Figure 2. Trends in mean daily maximum (AT_{MAX}), average (AT_{AVE}), and minimum (AT_{MIN}) temperatures and mean daily maximum (W_{MAX}), average (W_{AVE}), and maximum gust (G_{MAX}) windspeeds during July–August from 1996 to 2014 (statistical values of R^2 and p in top right corners of figures; Δ = total change for statistically significant trends; solid lines indicate statistical significance and dotted lines are non-significant).

Table 2. Total changes in the depths of 50% (TR_{50}), 25% (TR_{25}), and 1% (TR_1) light transmission by pond between 199 and 2014, and associated R^2 and p values of the regressions (significant results are highlighted). “All ponds” refers to mean values for the entire group of ponds.

	total change (m)			R^2			p		
	TR_{50}	TR_{25}	TR_1	TR_{50}	TR_{25}	TR_1	TR_{50}	TR_{25}	TR_1
Duck	0.68	0.62	0.32	0.14	0.06	0.00	0.14	0.35	0.87
Dyer	0.56	0.79	-2.44	0.25	0.21	0.19	0.04	0.06	0.08
Great-T	1.13	1.41	2.69	0.41	0.34	0.16	0.01	0.01	0.11
Great-W	0.90	1.12	-1.19	0.23	0.14	0.08	0.06	0.15	0.30
Gull	0.50	0.92	2.87	0.05	0.17	0.22	0.41	0.10	0.06
Herring	0.17	0.32	1.02	0.05	0.06	0.07	0.43	0.38	0.35
Long	1.63	2.24	5.05	0.52	0.50	0.40	0.00	0.00	0.01
Ryder	0.79	1.12	2.68	0.28	0.31	0.23	0.03	0.02	0.05
Slough	0.93	1.16	2.24	0.60	0.41	0.12	0.00	0.02	0.09
All ponds	0.52	0.67	1.36	0.48	0.52	0.24	0.01	0.01	0.09

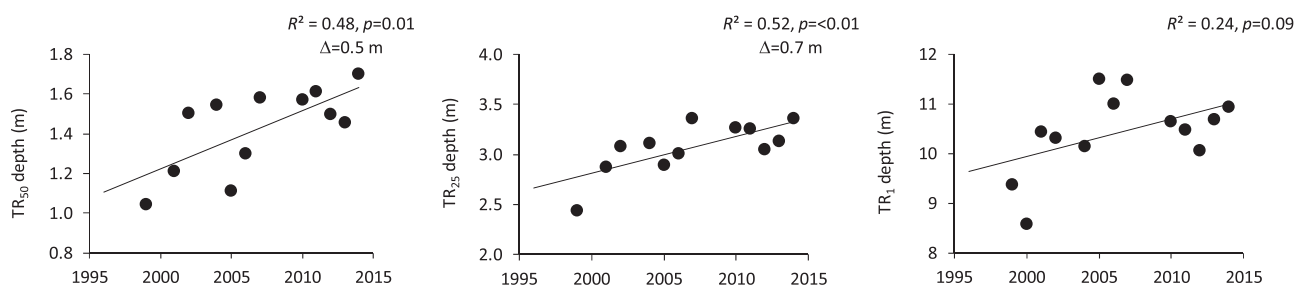


Figure 3. Mean (all ponds) depths of 50% (TR_{50}), 25% (TR_{25}), and 1% (TR_1) light transmission by year from 1999 to 2014 (statistical values of R^2 and p in top right corners of figures; Δ = total change for statistically significant trends; solid lines indicate statistical significance and dotted lines are nonsignificant).

Thermocline depths

Several significant trends in TC_D were measured among the ponds during August from 1996 to 2014 (Fig. 4). TC_D shoaled significantly in Dyer by 3.6 m and in Great-W by 3.5 m. By contrast, the thermocline deepened in Slough pond by 2.9 m. No other ponds exhibited statistically significant trends.

Surface–bottom water temperature differences

SB_{DIFF} increased significantly in Dyer, Great-W, Gull, Herring, and Slough ponds (Fig. 5). Total changes in this variable from 1996 to 2014 ranged between 1.8 °C (Gull) and 11.5 °C (Dyer). The large value for Dyer pond is the result of this pond being well mixed in the late 1990s. Duck, Great-T, Long, and Ryder ponds exhibited no temporal trends (Fig. 5).

Bottom water temperatures

Bottom waters generally cooled from 1996 to 2014, with statistically significant trends in Duck, Dyer, and Great-W ponds (Fig. 6). The bottom waters of these 3 ponds cooled by 3.0, 10.1, and 7.2 °C, respectively. The other ponds showed no significant increase or decrease in T_{BW} .

Schmidt stability

SS values increased significantly in Dyer, Great-W, Gull, and Ryder ponds by ≥ 69 J/m² (Fig. 7). Duck and Herring ponds also exhibited increasing trends, but p values were slightly higher than 0.05. The lack of bathymetric data for Long and Slough ponds precluded analyses of this variable.

Temporal trends in the grand means (average of all ponds) of temperature variables

The warming trends for individual ponds in July–August noted in Smith et al. (2016) were similarly manifested in the grand mean values of all ponds during August only from 1996 to 2014, warming by 0.9 °C; however, the variability was such that the regression was not statistically significant (Fig. 8). Thermocline depth shoaled by 0.7 m (not significant) and T_{BW} cooled by 3.1 °C, respectively, between 1996 and 2014 while temperature differentials between surface and bottom waters significantly increased by 4 °C. Thermal stability, as indicated by SS values, exhibited a large, significant increase of 62.4 J/m². Changes in vertical temperature structure are illustrated for Duck, Dyer, and Great-W ponds between 1996 and 2014 in Fig. 9.

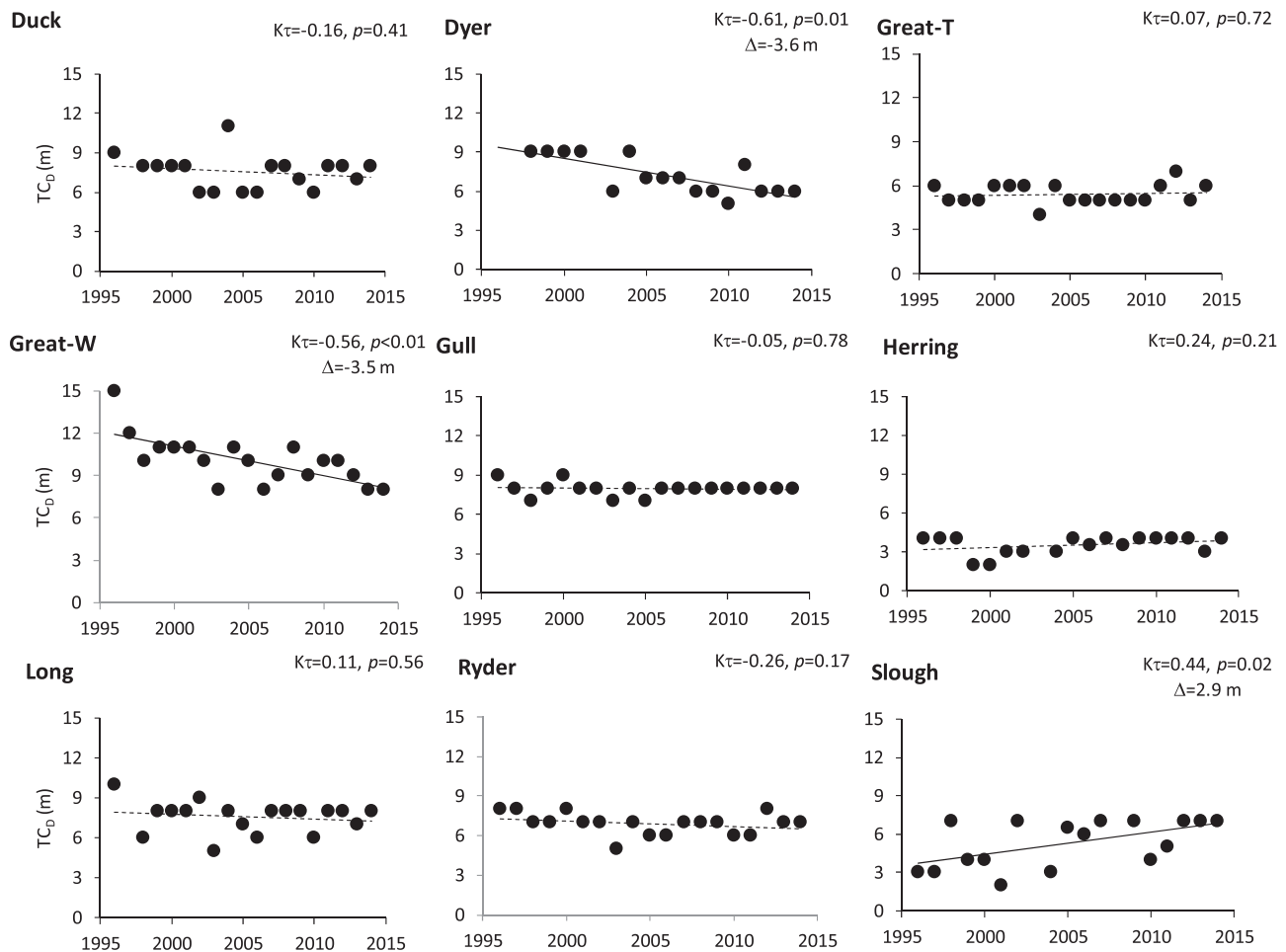


Figure 4. Trends in thermocline depth (TC_D) depth by pond from 1996 to 2014 (statistical values of R^2 and p in top right corners of figures; Δ = total change for statistically significant trends; solid lines indicate statistical significance and dotted lines are nonsignificant).

Correlations of temperature variables with physical attributes of ponds

When absolute and percent changes in temperature variables from 1996 to 2014 were compared with the physical attributes of the ponds, no significant correlations emerged (data not shown). By contrast, when temperature variables from the most recent data (2014) were analyzed in relation to physical attributes, a number of significant relationships were evident (Table 3). For example, TC_D , SB_{DIFF} and SS were positively and significantly related to maximum depth, whereas T_{BW} was negatively related. T_{BW} and SS were also negatively and positively related to pond volume, respectively. TC_D and SS exhibited significant positive correlations with pond area and mean depth, respectively. No temperature variables were significantly related to pond aspect ratio.

Correlations between light transmission and temperature variables

Strong, positive correlations were found between transmission variables and thermocline depths among ponds

within individual years (Table 4, Fig. 10). Specifically, TC_D was significantly related to the depths for all transmission variables. The other temperature variables generally exhibited weak, insignificant relationships (data not shown).

Correlations of pond temperature variables with mean daily air temperatures

Temperature variables exhibited stronger relationships with July AT_{MIN} than AT_{MAX} or AT_{AVE} . T_{SW} , TC_D , and SS values showed significant correlations with AT_{MIN} , whereas SB_{DIFF} and T_{BW} did not (Fig. 11). While T_{SW} , SB_{DIFF} and SS were all positively correlated with AT_{MIN} , TC_D and T_{BW} were negatively correlated.

Discussion

The analysis of temperature profiles in this study revealed trends that indicate enhanced thermal stability of CCNS kettle ponds during August, as evidenced by increasing SS values, widening temperature differentials at the thermocline, and increased divergence between surface and

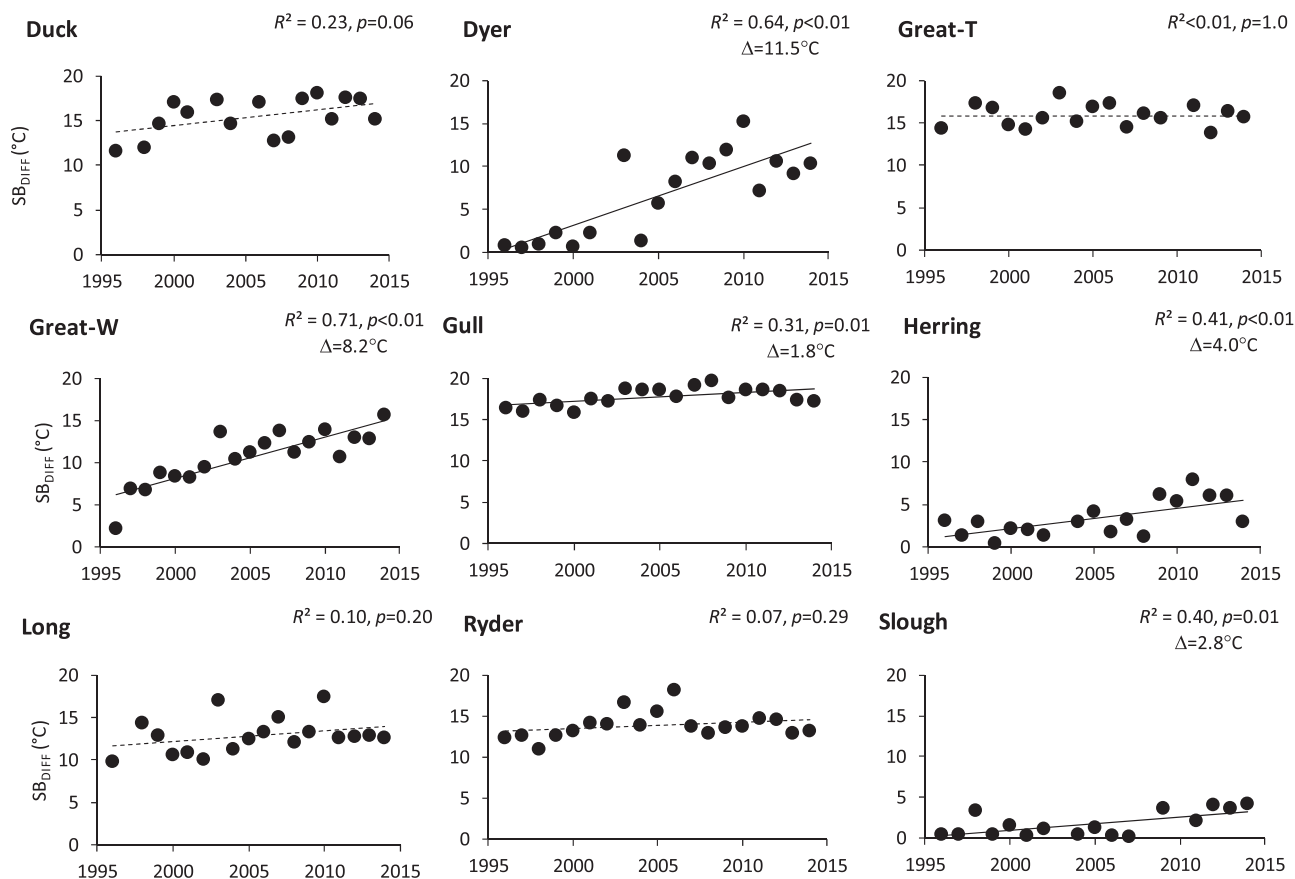


Figure 5. Trends in temperature differences between surface and bottom waters (SB_{DIFF}) by pond from 1996 to 2014 (statistical values of R^2 and p in top right corners of figures; Δ = total change for statistically significant trends; solid lines indicate statistical significance and dotted lines are nonsignificant).

bottom water temperatures. These changes are likely being driven by local air temperatures, which have exhibited a steady rise since 1973 (Smith et al. 2016), and declining wind speeds, both of which strengthen thermal stratification. Another factor that can influence thermal properties of lakes is the amount of solar radiation they receive, which may vary with decadal-scale changes in air pollution (Edinger et al. 1968). Although such data were not available for outer Cape Cod, a slight declining trend has been noted in nearby Boston, Massachusetts, over recent decades (based on analysis of 1990–2010 data from the National Solar Radiation Database; <http://rredc.nrel.gov>). Similarly, Liepert (2002) calculated a 10% reduction in solar radiation across the United States due mainly to increasing cloud cover. Accordingly, this factor does not seem to have played a major role in the observed thermal changes for CCNS ponds.

Some lakes exhibited statistically significant trends in various thermal properties while others did not. Many studies have reported that specific physical features, especially size, have an influence on lake properties (Read et al. 2012, Woolway et al. 2016); however, no significant relationships were found between changes in any of the

temperature variables and pond area, mean/maximum depth, volume, or aspect ratio. Although others have found that deeper lakes can apparently experience larger changes in lake stratification than shallower lakes (e.g., Kraemer et al. 2015), such relationships were not evident in this study. Notwithstanding, when the actual temperature values (instead of absolute or percent change values) from the most recent sampling in 2014 were analyzed, many did exhibit relationships with lake morphometry, particularly with maximum depth and volume. For example, TC_D , SB_{DIFF} and SS values were larger with increasing maximum pond depth and volume, suggesting that larger, deeper ponds exhibit stronger stratification.

Shoaling of the thermocline, which was observed in Dyer and Great-W ponds, has been reported previously (Freeland et al. 1997, Alcocer and Lugo 2003). In these 2 ponds, TR_1 depths decreased from 1996 to 2014 (although not significantly in Great-W), indicating reduced penetration of the last remaining light. The reason for this is unknown, and all other ponds exhibited increasing transmissivity. Possibly, warming and/or diminished wind speeds shifted the thermocline above the typical TR_1 depth, and therefore light transmission in this depth range

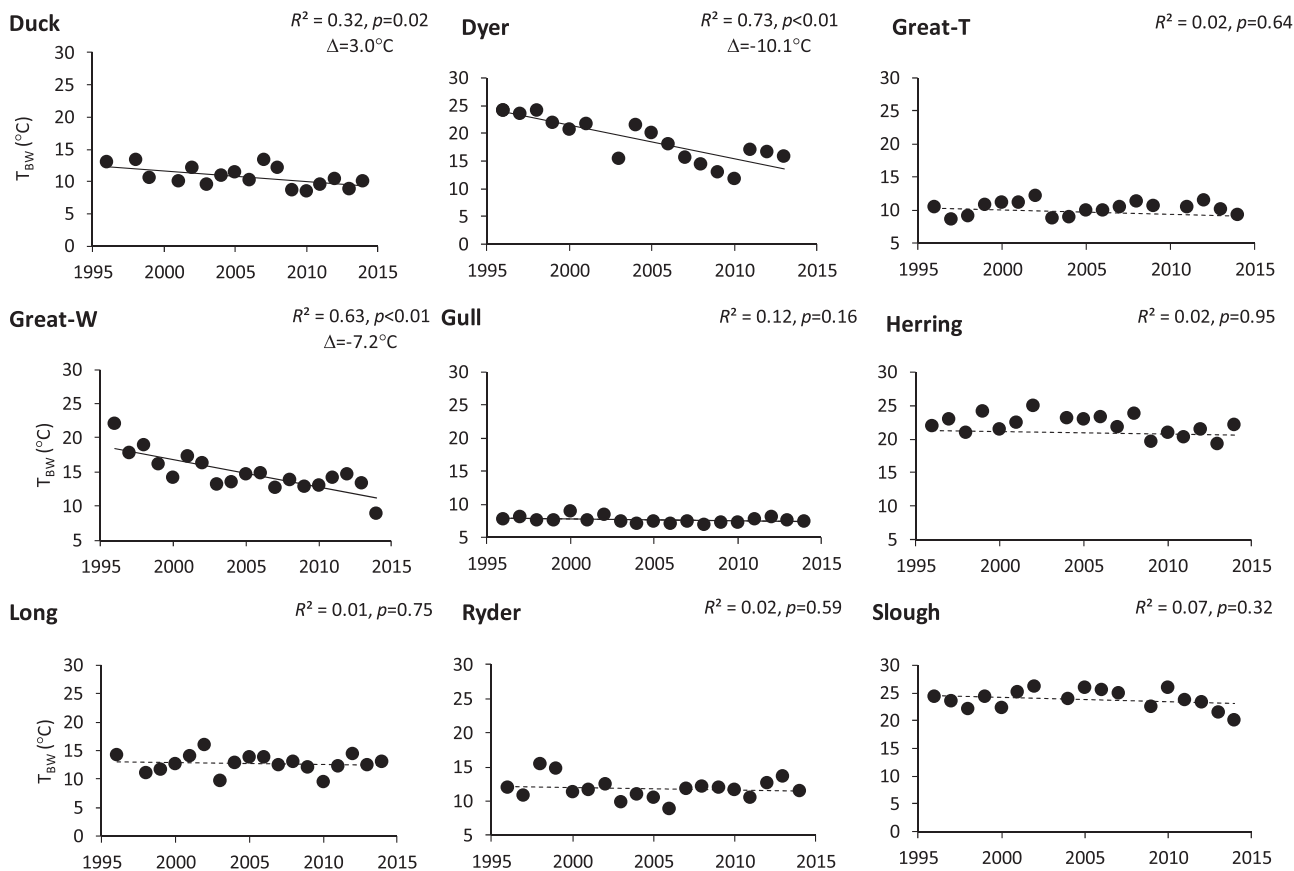


Figure 6. Trends in bottom water temperatures (T_{BW}) by pond from 1996 to 2014 (statistical values of R^2 and p in top right corners of figures; Δ = total change for statistically significant trends; solid lines indicate statistical significance and dotted lines are nonsignificant).

lowered. With respect to the wind climate, the vegetation surrounding these ponds has been protected from cutting and clearing since 1961 when the park was established. Thus, unimpeded forest growth over the last 56 years must be physically reducing wind speeds across these ponds.

In addition to phytoplankton, light is attenuated in the water column by DOC, which is increasing in many lakes throughout the northeast because of reductions in acidity (Keller et al. 2008, SanClements et al. 2012, Smith et al. 2016). Recent measurements of optical absorbance of ultraviolet radiation (254 nm), a proxy for total DOC concentration (Deflandre and Gagné 2001), indicate that DOC in CCNS pond surface waters is very low at <3 mg/L, with large variability among ponds (SMS, unpubl. data). Even clear lakes, however, can exhibit large thermal changes in response to small differences in DOC (Gunn et al. 2001, Snucins and Gunn 2000) and may be more thermally sensitive to climate change (Read and Rose 2013). Hence, changes in DOC concentrations in these ponds may be influencing thermal structure, but this is only speculation in the absence of long-term DOC data. In most ponds, which exhibited increasing transmissivity over time, enhanced thermal stratification may be

causing seasonal oligotrophy of the epilimnion (Fee 1980, Nürnberg and Shaw 1998).

From the standpoint of biogeochemical and biological consequences of altered thermal properties, declining bottom water temperatures may reduce rates of microbial decomposition and oxygen consumption at depth. The decreasing bottom water temperatures observed in this study are similar to those of other freshwater lakes, especially small lakes (e.g., Hondzo and Stefan 1993, Alcocer and Lugo 2003, Winslow et al. 2015), likely because of, in part, the reduction in local summertime wind speeds (Fig. 2) and, at an individual pond level, further diminishment of winds from surrounding forest growth. Regardless, this trend has been observed in many regions across the United States (Pryor et al. 2009). The resulting thermal stability may translate to lower rates of internal phosphorus release from lake sediments, although this process is extremely complex and depends on a large number of other factors (Hupfer and Lewandowski 2008, Loh et al. 2013, Liang et al. 2015). Reduced bottom water temperatures in some ponds may also have an effect on carbon cycling, with higher rates of carbon burial in deep sediments since the respiration of organic matter to produce carbon dioxide

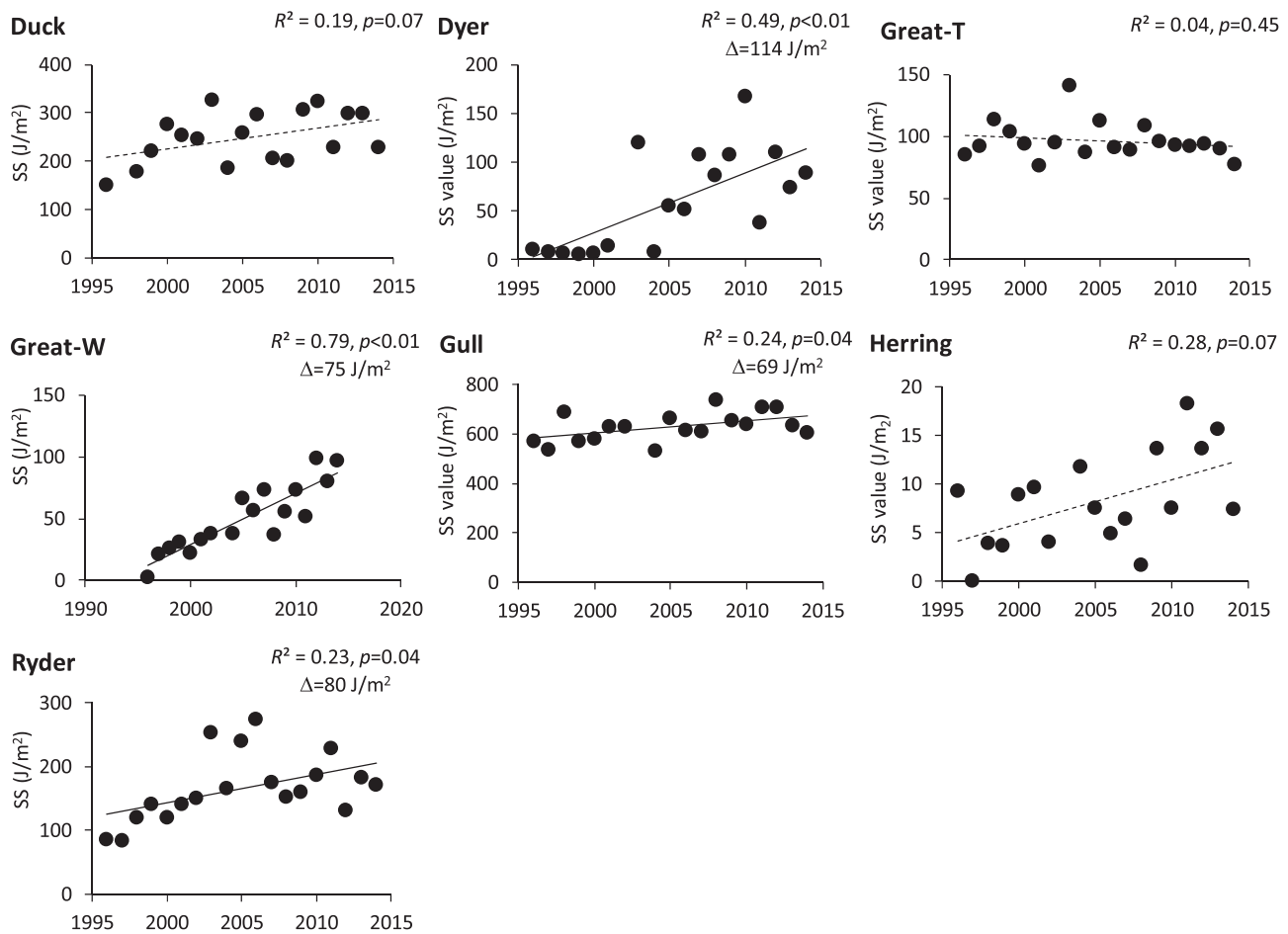


Figure 7. Schmidt stability (SS) values between 1996 and 2014 for ponds with bathymetric data.

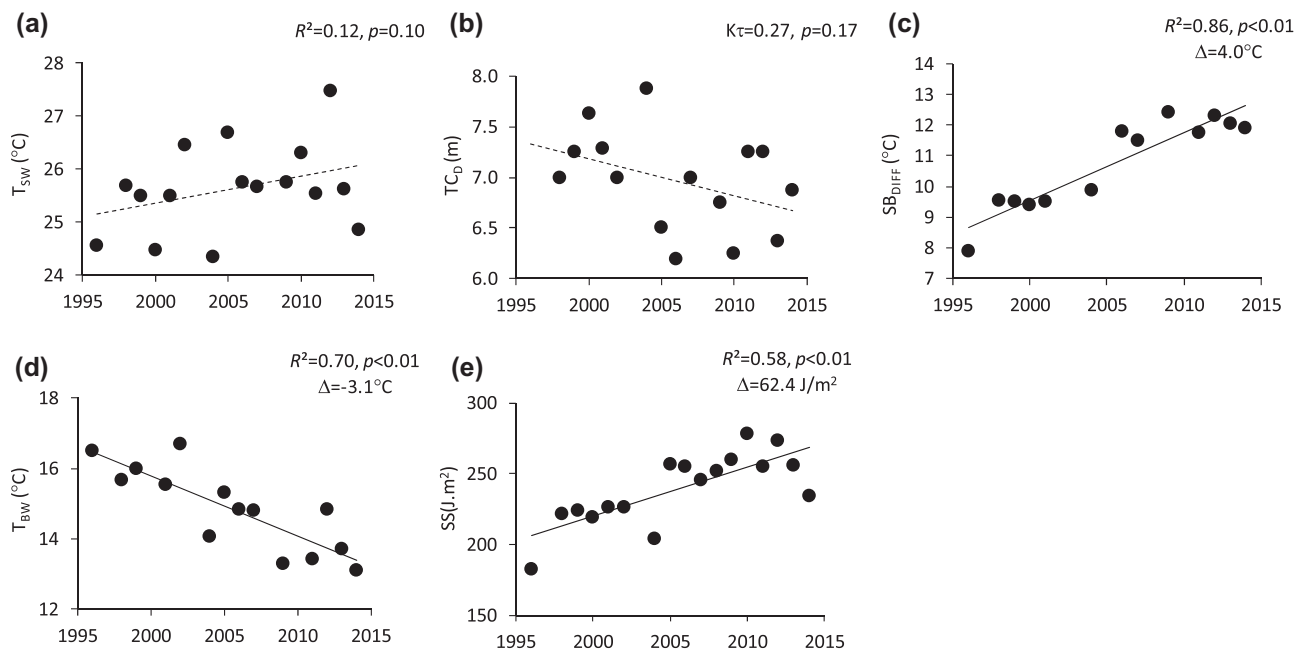


Figure 8. Trends in the grand means (all ponds) of (a) surface water temperatures (T_{SW}), (b) thermocline depth (TC_D), (c) temperature difference across the thermocline (TC_{DIFF}), (d) difference in temperature between surface and bottom waters (SB_{DIFF}), (e) bottom water temperatures (T_{BW}), and (f) Schmidt stability (SS) values from 1996 to 2014 (statistical values of R^2 and p in top right corners of figures; Δ = total change for statistically significant trends; solid lines indicate statistical significance and dotted lines are nonsignificant).

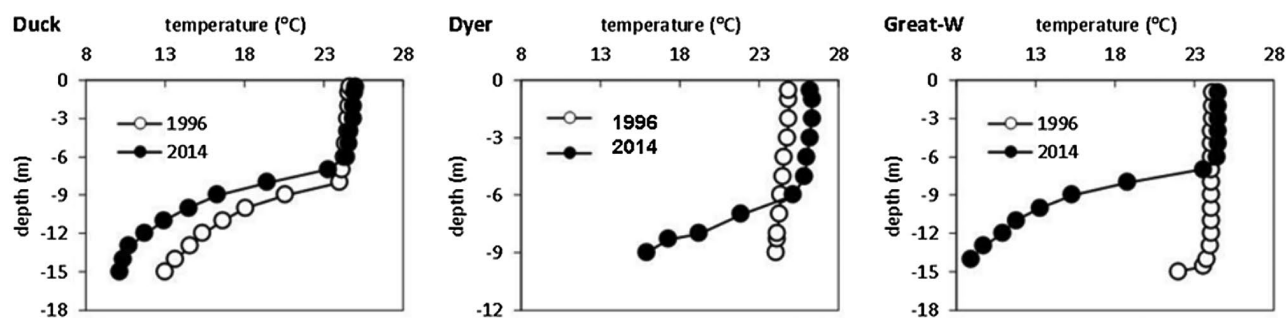


Figure 9. Comparisons of temperature profiles in Duck, Dyer, and Great-W ponds in August 1996 vs. August 2014.

Table 3. Kendall τ and statistical probability (in parentheses) values for correlations between thermal variables from 2014 and pond physical attributes (T_{SW} = surface water temperature, TC_D = thermocline depth, T_{BW} = bottom water temperature, SB_{DIFF} = temperature difference between surface and bottom water, and SS = Schmidt stability). Highlighted cells indicate statistically significant relationships.

	area	max depth	mean depth	volume	aspect ratio
T_{SW}	-0.06 (0.83)	0.14 (0.60)	0.11 (0.67)	0.22 (0.40)	-0.22 (0.40)
TC_D	0.19 (0.51)	0.67 (0.02)	0.44 (0.12)	0.44 (0.12)	-0.19 (0.51)
T_{BW}	-0.56 (0.04)	-0.70 (<0.01)	-0.06 (0.83)	-0.61 (0.02)	-0.28 (0.30)
SB_{DIFF}	0.44 (0.09)	0.70 (<0.01)	0.06 (0.83)	0.50 (0.06)	0.17 (0.53)
SS	0.24 (0.45)	0.68 (0.03)	0.91 (<0.01)	0.62 (0.05)	-0.05 (0.88)

Table 4. Statistical R^2 values for regressions of transmission variables (TR_{50} , TR_{25} , and TR_1) with thermocline depths across all ponds for 1999–2014 (highlighted values are statistically significant at $\alpha = 0.05$).

	TR_{50}	TR_{25}	TR_1
1999	0.20	0.52	0.77
2000	0.40	0.56	0.82
2001	0.01	0.53	0.58
2002	0.20	0.69	0.90
2003	0.24	0.88	0.59
2004	0.41	0.47	0.51
2005	0.22	0.53	0.29
2006	0.54	0.53	0.74
2007	0.36	0.64	0.86
2008	0.61	0.79	0.50
2009	0.80	0.80	0.71
2010	0.59	0.70	0.23
2011	0.52	0.67	0.55
2012	0.16	0.40	0.32
2013	0.18	0.61	0.53
2014	0.34	0.58	0.50

and methane occurs more slowly at lower temperatures (Gudasz et al. 2010, Yvon-Durocher et al. 2011, 2014, Rasilo et al. 2015). Studies of lake sediments have shown that lakes are important carbon sinks (Yvon-Durocher et al. 2011, 2014, Heathcote et al. 2015, Rasilo et al. 2015).

Algal species composition, seasonal patterns of productivity, and taxonomy may also be affected by changing thermal profiles (Findlay et al. 2001, Winder and Sommer 2012). In many cases, lake warming has led to, or is predicted to lead to, increased dominance of cyanobacteria (Paerl and Huisman 2009, Carey et al. 2012, Posch et al. 2012). Toxic blooms of these algae have received considerable local attention in recent years (Cape Cod Times:

4 Aug 2009, 30 Jul 2013, 8 Aug 2014, 1 Sep 2015), and taxonomic analysis of phytoplankton samples from 10 CCNS kettle ponds in 2006 indicated that cyanobacteria comprised 3% to 96% of the communities (SMS, unpubl. data). Further impacts of these thermal changes may include mismatches in the timing of algae–zooplankton blooms (Peeters et al. 2007, Winder and Sommer 2012) and changes in the suitability of various thermal habitats (i.e., stenotherms) for various aquatic organisms, including fish (King et al. 1999, Wrona et al. 2006, Healey 2011).

In conclusion, this study suggests that over the last ~2 decades the seasonal stratification of CCNS kettle ponds has strengthened considerably. Given that these ecosystems are important natural and cultural resources, this information may help park management understand how these ecosystems currently function, how they have evolved over the recent past, and what their future trajectory may be with continued climate change. We further hypothesize that various biological processes, ranging from algal productivity to fish population dynamics, have been altered by these temperature shifts. The changes seem to be the result of broader climate trends and are therefore not manageable at the park level; however, limiting additional impacts (e.g., shoreline trampling and bank erosion, nutrient inputs from wastewater systems, exotic species infestations) is essential in CCNS because various aspects of climate change likely interact synergistically with these other stressors (Woodward et al. 2010). Undertaking such ground-level management could significantly benefit these sensitive ecosystems that are otherwise exposed to larger-scale anthropogenic pressures.

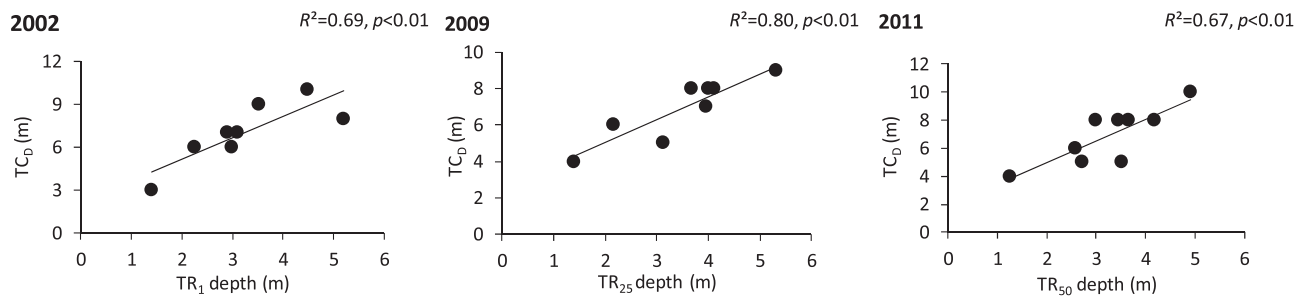


Figure 10. Thermocline depths (TC_D) as a function of the depth of 50% (TR_{50}), 25% (TR_{25}), and 1% (TR_1) light transmission for select years (2002, 2009, 2011); (statistical values of R^2 and p in top right corners of figures; solid lines indicate statistical significance and dotted lines are nonsignificant).

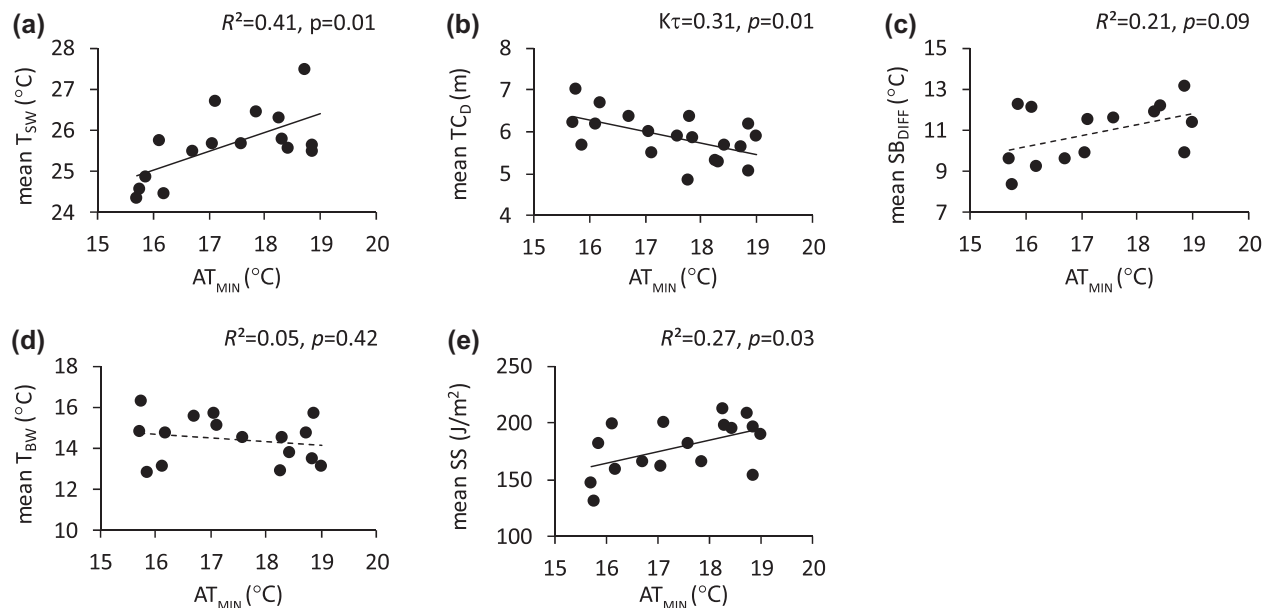


Figure 11. Linear relationships between the grand means of (a) surface water temperature (T_{SW}), (b) thermocline depth (TC_D), (c) difference between surface and bottom water temperatures (SB_{DIFF}), (d) bottom water temperatures (T_{BW}), and (e) Schmidt stability (SS) with minimum daily air temperatures in July (AT_{MIN}); (statistical values of $K\tau$, R^2 and p indicated in top right corners of figures; solid lines indicate statistical significance and dotted lines are nonsignificant).

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